

Enhanced spin pumping into superconductors provides evidence for superconducting pure spin currents

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Unlike conventional spin-singlet Cooper pairs, spin-triplet pairs can carry spin.^{1,2} Triplet supercurrents were discovered in Josephson junctions with metallic ferromagnet (FM) spacers, where spin transport can only occur within the FM and in conjunction with a charge current. Ferromagnetic resonance (FMR) injects a pure spin current from a precessing FM into adjacent non-magnetic materials.^{3,4} For spin-singlet pairing, FMR spin pumping efficiency decreases below the critical temperature (T_c) of a coupled superconductor (SC).^{5,6} Here we present FMR experiments in which spin sink layers with strong spin-orbit coupling are added to the SC. Our results show that the induced spin currents, rather than being

25 **suppressed, are substantially larger in the superconducting state compared with**
26 **the normal state; although further work is required to establish the details of the**
27 **spin transport process we show that this cannot be mediated by quasiparticles and**
28 **is most likely a triplet pure spin supercurrent.**

29

30 Direct spin transport studies in SCs⁷⁻¹⁰ have traditionally involved quasiparticle (QP)
31 injection at bias voltages around the superconducting gap energy. A number of exotic
32 properties have been observed: enhanced spin relaxation time¹¹⁻¹³, spin and charge
33 decoupling^{9,10} and a giant spin-orbit interaction¹⁴. Equilibrium (zero-bias) studies^{1,2} of
34 the Josephson effect in SC/FM/SC junctions and T_c modulation in FM/SC/FM and
35 SC/FM/FM' superconducting spin valves have demonstrated that engineered
36 magnetically-inhomogeneous (spin-mixing) SC/FM interfaces can generate triplet
37 pairing states. However, direct measurement of triplet spin transport through singlet SCs
38 has not so far been achieved.

39 A time-dependent ferromagnetic magnetization generates a spin angular
40 momentum flow into adjacent materials (spin pumping)^{3,4}, and the transport and
41 relaxation of spin currents from the FM in turn affects its magnetization dynamics via
42 an enhancement in the (effective) Gilbert damping α (Fig. 1a). Using this FMR method
43 it was previously demonstrated⁵ that Andreev reflection, in which the incident electron
44 across the FM/SC interface is coherently coupled with the retro-reflection of a hole to
45 generate a (spin-zero) spin-singlet Cooper pair in the SC, essentially excludes the
46 transport of dynamically-driven spin currents through the superconducting gap 2Δ (Fig.
47 1b) and so the spin-current-induced broadening of the FMR linewidth is suppressed by
48 the development of the superconducting state⁶.

49 In this paper, we compare FMR results on Nb/Ni₈₀Fe₂₀/Nb trilayers with
50 Pt/Nb/Ni₈₀Fe₂₀/Nb/Pt structures in which the Pt provides an effective spin sink with
51 strong spin-orbit coupling (SOC). To explore the influence of superconductivity on spin
52 transport we measured the temperature (T) evolution of the FMR spectra [e.g. the
53 linewidth $\mu_0\Delta H$ (proportional to α) and the resonance field $\mu_0 H_{\text{res}}$; see Supplementary
54 Information (Sec. S1) for full details] across T_c . Where Pt (or other large SOC spin
55 sinks) are present, a substantially increased FMR damping for SC layer thicknesses of
56 the order of the coherence length ξ_{sc} is interpreted as evidence for the generation of
57 superconducting spin currents.

58 Figure 2a shows $\mu_0\Delta H(T)$ for Nb/Ni₈₀Fe₂₀/Nb trilayers with several Nb
59 thicknesses t_{Nb} at a fixed microwave frequency $f = 20$ GHz. For all t_{Nb} , $\mu_0\Delta H$ is almost
60 T -independent between 10 and 100 K. All the samples show a slight upturn in $\mu_0\Delta H$
61 with decreasing T around 10 K. Since this also occurs for the non-superconducting
62 sample ($t_{\text{Nb}} = 7.5$ nm), this must reflect intrinsic normal state properties of the coupled
63 system and be unrelated to peaks in $\mu_0\Delta H$ predicted below T_c associated with the onset
64 of superconductivity^{6,14}. As T is reduced further, a significant t_{Nb} -dependent reduction
65 of $\mu_0\Delta H$ occurs which is explained by the inhibition of singlet spin transport in the
66 SC^{5,6,14}. To quantitatively characterize the overall behaviour, we plotted $\mu_0\Delta H(t_{\text{Nb}})$ for
67 various T between 2 and 80 K (Fig. 2b). For all T , $\mu_0\Delta H(t_{\text{Nb}})$ is approximately
68 exponential, as expected for diffusive spin transport^{3,4}. However, when $T < 8$ K
69 (entering the superconducting state), $\mu_0\Delta H$ saturates faster to a smaller asymptotic
70 value, implying that, below T_c , the transfer efficiency of spin across the Ni₈₀Fe₂₀/Nb
71 interfaces and the characteristic length of spin transport in the Nb are both reduced^{3,4}.
72 This can be quantified, as discussed in Supplementary Information (Sec. S3).

73 The key aim of this work is to explore how this superconducting spin-blocking
 74 behaviour is modified when an effective spin sink is placed beyond the SC layers.
 75 Figure 2c shows $\mu_0\Delta H(T)$ for Pt/Nb/Ni₈₀Fe₂₀/Nb/Pt structures with different t_{Nb} . The
 76 most important aspect of the data is the remarkable enhancement of magnetization
 77 damping for the intermediate t_{Nb} of 15 and 30 nm at low T when attached to Pt layers.
 78 Note that for the thicker superconducting Nb layers (45 and 60 nm), the T dependence
 79 of $\mu_0\Delta H$ is qualitatively similar to the samples without the Pt layers (Fig. 2a). For
 80 comparison with Fig. 2b, we show in Fig. 2d $\mu_0\Delta H(t_{\text{Nb}})$ for different (constant) T
 81 ranging from 80 to 2 K. There is a clear enhancement of $\mu_0\Delta H$ in the superconducting
 82 state for the $t_{\text{Nb}} = 15$ and 30 nm samples. The change in $\mu_0\Delta H$ between the normal and
 83 superconducting states is shown in the upper inset of Fig. 2d which contains data for
 84 other t_{Nb} and shows a systematic enhancement up to $t_{\text{Nb}} = 30$ nm followed by a fall for
 85 larger thicknesses.

86 Before discussing the likely explanation for this enhancement of spin transport in
 87 the superconducting state, we first consider the normal state using the spin pumping
 88 model^{3,4} for composite spin sinks:

$$89 \quad \alpha_{sp}^c(t_{SC}) = 2 \cdot \left(\frac{g_L \mu_B g_r^{\uparrow\downarrow}}{4\pi M_s t_{FM}} \right) \cdot \left[1 + g_r^{\uparrow\downarrow} \mathcal{R}_{SC} \cdot \left(\frac{1 + g_{SC} \tanh\left(\frac{t_{SC}}{l_{sd}^{SC}}\right)}{\tanh\left(\frac{t_{SC}}{l_{sd}^{SC}}\right) + g_{SC}} \right) \right]^{-1}, \quad (1)$$

90 where g_L is the Landé g-factor, μ_B is the Bohr magneton, and \hbar is Plank's constant
 91 divided by 2π . $g_r^{\uparrow\downarrow}$ is the (effective) spin mixing conductance of the Ni₈₀Fe₂₀/Nb
 92 interface and g is the (effective) spin transfer conductance of the Nb/Pt interface (~ 35
 93 nm⁻²)^{3,15}. $\mathcal{R}_{SC} \equiv \rho_{SC} l_{sd}^{SC} e^2 / 2\pi\hbar$ is the spin resistance of the Nb layer where ρ_{SC} is the
 94 resistivity of the Nb [see Supplementary Information (Sec. S3)], l_{sd}^{SC} is the spin diffusion
 95 length of the Nb, and e is the electron charge. t_{FM} is the Ni₈₀Fe₂₀ thickness and M_s is its

96 saturation magnetization. For $T \geq 8$ K, the universal trend of decreasing $\mu_0\Delta H$ with
 97 increasing t_{Nb} is well fitted by this model (Fig. 2d, solid lines). This is a result of the
 98 progressively increased screening of the Pt spin sink from the $\text{Ni}_{80}\text{Fe}_{20}$ spin source as
 99 the Nb layer thickness increases, the Nb having a modest spin conductance [$3.5 - 5.0$
 100 nm^{-2} , see Supplementary Information (Sec. S3)]. The extracted values of $g_r^{\uparrow\downarrow}$ ($\sim 10 \text{ nm}^{-2}$)
 101 and l_{sd}^{SC} ($35 - 45 \text{ nm}$) are also in good agreement with those obtained from the samples
 102 without Pt layers [$g = 0$, see Figs. 2b and S3 (Supplementary Information)] and, for
 103 l_{sd}^{SC} , with Ref.¹⁶. It can be seen that the FMR linewidth tends to the same value at large
 104 t_{Nb} for samples with and without the Pt spin sinks as would be expected once spin
 105 transport to the Pt is blocked.

106 For the superconducting state, we consider first the samples without the Pt spin
 107 sinks. The transmission of non-equilibrium spin accumulation generated on the FM side
 108 to the nonmagnetic layer depends on the matching of the electronic band structures in
 109 the two materials on either side of the interface^{17,18}, which can be quantified as follows:

$$\begin{aligned}
 110 \quad \mathcal{T} = \frac{g_0^{\uparrow\downarrow}}{g_0^{\uparrow\downarrow} + \left(\frac{1}{\mathcal{R}_{FM}} \cdot \tanh\left(\frac{t_{FM}}{l_{sd}^{FM}}\right) \right)} ; \quad g_0^{\uparrow\downarrow} = \frac{g_r^{\uparrow\downarrow} \cdot \left(\frac{1}{\mathcal{R}_{FM}} \cdot \tanh\left(\frac{t_{FM}}{l_{sd}^{FM}}\right) \right)}{\left(\frac{1}{\mathcal{R}_{FM}} \cdot \tanh\left(\frac{t_{FM}}{l_{sd}^{FM}}\right) \right) - g_r^{\uparrow\downarrow}} \quad (2)
 \end{aligned}$$

111 where $\mathcal{R}_{FM} \equiv \rho_{FM} l_{sd}^{FM} e^2 / 2\pi\hbar$, ρ_{FM} is the resistivity ($20 \mu\Omega\text{-cm}$ for $T \leq 10$ K, $30 \mu\Omega\text{-cm}$
 112 at 300 K) of the $\text{Ni}_{80}\text{Fe}_{20}$ ¹⁹, and l_{sd}^{FM} is the spin diffusion length (5 nm for $T \leq 10$ K, 4
 113 nm at 300 K). Note that $g_0^{\uparrow\downarrow}$ is the actual spin mixing conductance. \mathcal{T} is calculated to be
 114 0.34 , 0.34 , 0.51 , and 0.59 at 2 , 4 , 8 , and 300 K, respectively, using Eq. (2). We can then
 115 see that the spin transparency of the $\text{Ni}_{80}\text{Fe}_{20}/\text{Nb}$ interface is much lower when the Nb is
 116 superconducting, supporting that the reduced spin-injection efficiency which is ascribed
 117 to the band structure mismatch due to the presence of the energy gap 2Δ . For the

118 transport length l_{qp}^{sp} of dynamically-driven spin-polarized QPs in the diffusive [$t_{Nb} >$
 119 l_{mfp} , where l_{mfp} is the mean free path of the Nb (6 nm)] and low T condition ($T/T_c \leq$
 120 0.3)¹⁶, one has to take into account the conversion time τ_{AR} of QPs into (spin-singlet)
 121 Cooper pairs by Andreev reflection in addition to their spin lifetime τ_{sf} :

$$122 \quad l_{qp}^{sp} = \sqrt{D \cdot \left(\frac{1}{\tau_{AR}} + \frac{1}{\tau_{sf}} \right)^{-1}} \quad (3)$$

123 where D is the diffusion coefficient of the Nb. Considering that τ_{AR} (for low energy
 124 QPs) is much shorter than τ_{sf} as Andreev reflection is fundamentally the interfacial
 125 conversion process, Eq. (3) can be simplified to $l_{qp}^{sp} \approx \sqrt{D\tau_{AR}}$, which therefore can be
 126 comparable to ξ_{sc} .¹⁶ In fact, we find that the estimated l_{qp}^{sp} of ~ 21 nm at 2 K is of the
 127 order of the zero-temperature ξ_{sc} of Nb (13 nm) in the dirty limit, given by
 128 $0.85\sqrt{l_{mfp} \cdot \xi_0}$ where ξ_0 is the clean-limit coherence length of Nb (38 nm). We note
 129 that in a previous experiment of the magnetoresistance of an $Ni_{80}Fe_{20}/Nb/Ni_{80}Fe_{20}$ spin
 130 valve¹⁶, the penetration length of spin-polarized QPs through superconducting Nb was
 131 measured to be ~ 16 nm under low T and DC bias conditions.

132 This general behaviour is replicated by the $t_{Nb} = 45$ and 60 nm
 133 Pt/Nb/ $Ni_{80}Fe_{20}$ /Nb/Pt samples (Fig. 2c) in that the transport of spin-polarized QPs is
 134 blocked by Andreev reflection. The anomalous Pt/Nb/ $Ni_{80}Fe_{20}$ /Nb/Pt samples ($t_{Nb} = 15,$
 135 22.5, 30 and 37.5 nm, Fig. 2d) behave in an exactly opposite way in that the FMR
 136 linewidth and hence spin transport to the Pt is progressively *enhanced relative to the*
 137 *normal state* with decreasing T .

138 The enhanced spin cannot carried by QP currents even if one assumes an
 139 unexpected increase in the low T spin diffusion length because the available QP states
 140 will progressively freeze out at a lower T , as demonstrated by our own measurements of

141 Nb/Ni₈₀Fe₂₀/Nb samples as well as the existing theories of QP-mediated spin
 142 transport^{5,6}. It should be noted that the significant enhancement of FMR linewidth
 143 predicted for *insulating* FM/SC⁶ occurs only close to T_c and is strongly suppressed for
 144 conducting FM materials. The existing theory for FMR in metallic FM/SC systems also
 145 shows a significant damping of QP spin transport even if a spin sink layer is added to
 146 the SC⁵. Thus the monotonic enhancement of spin transport with decreasing T for the
 147 intermediate t_{Nb} must involve supercurrents. The mechanisms enabling supercurrent-
 148 mediated spin transport through a singlet SC are crossed Andreev reflection (CAR),
 149 elastic co-tunneling (EC), or an induced triplet pairing state²⁰. CAR and EC via spin-
 150 singlet supercurrents require the involvement of (unpaired) electrons within 2Δ in both
 151 the FM and the spin sink. In order to distinguish between these mechanisms, we have
 152 replaced the Pt with a range of other spin sink materials for fixed $t_{\text{Nb}} = 30$ nm (Fig. 3a).
 153 Of the materials used: 5 nm-thick Ta proximity-coupled to Nb should have an induced
 154 gap almost equal to that of the Nb²¹ and much larger than the spin-splitting of the
 155 electrochemical potentials $\Delta\mu$ (a few μeV) induced by spin pumping at the Ni₈₀Fe₂₀/Nb
 156 interface [see Supplementary Information (Sec. S7) for details] which eliminates the
 157 CAR and EC processes; in contrast, Fe₅₀Mn₅₀ strongly suppresses the Nb gap²² and so
 158 makes these processes more possible. The experimental results (Fig. 3b), which show
 159 superconducting spin transport relative to the normal state strongly enhanced by Ta and
 160 suppressed by Fe₅₀Mn₅₀, are therefore incompatible with these processes. The
 161 remaining possibility is therefore that the spin is carried via spin-triplet supercurrents.

162 A variety of mechanisms for generating triplet states have been proposed: static
 163 magnetic-inhomogeneity at the SC/FM interface²³⁻²⁵, SOC in conjunction with an
 164 exchange field^{26,27}, and the precession of interface magnetization^{28,29}; in all cases long-
 165 ranged triplet pairs (generated at the SC interface) should also penetrate into the SC side

166 and decay over the length scale of ξ_{SC} . Since our structures contain a single
167 homogeneous FM layer which is precessing coherently, the first mechanism appears to
168 be irrelevant.

169 It is interesting to note that in addition to strong SOC, Pt is close to a
170 ferromagnetic instability which induces a high spin susceptibility³⁰; therefore in this
171 case, a corrective term including the electron-electron interactions would need to be
172 taken into account in any rigorous theoretical model²⁶⁻²⁹. Such a term, which is always
173 present in real metallic materials, but is enhanced in Pt, leads to a non-negligible spin-
174 splitting in the Pt layer resulting from the short-range triplet correlations and the spin
175 penetration². Our preliminary calculations suggest that in this scenario, long-range spin-
176 triplet correlations would then be produced across the Nb layer between the precessing
177 $\text{Ni}_{80}\text{Fe}_{20}$ and the spin-split Pt giving rise to an additional spin-polarized supercurrent
178 below T_c . This additional spin supercurrent would be expected to increase below T_c and
179 decreases with a thicker Nb layer, consistent with our experimental observations. Our
180 experiments on other materials (Fig. 3b) show that the elements with large SOC (Pt, W,
181 Ta)³¹ reveal a large enhancement compared with the other materials, implying that SOC,
182 possibly acting in conjunction with a spin-splitting due to Fermi liquid effects may
183 provide the underlying explanation.

184 We have shown that FMR spin pumping into singlet SCs terminated by a large
185 (SOC) spin sink more efficiently transfers angular momentum than in the normal state.
186 Although detailed theories need to be developed to explain these results, we have
187 demonstrated that the spin currents cannot be carried by quasiparticles and are most
188 likely carried by spin-triplet pairs. We believe that the results presented in this paper
189 provide evidence for spin-polarized supercurrents in SCs.

190 **Methods**

191 Methods and any associated references are available in the online version of the
192 paper.

193

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- 274

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277

278 **Author contributions**

279 K.-R.J. and M.G.B. conceived and designed the experiments; The samples were
280 prepared by K.-R.J, with help and sputtering system provided by J.W.A.R. and M.G.B;
281 The FMR measurements were carried out by K.-R.J. with help of C.C., H.K. and A.J.F.;
282 The model calculation was done by X.M. and M.E. whereas the data analysis was done
283 by K.-R.J., C.C., H.K., J.W.A.R. and M.G.B.; All authors discussed the results and
284 commented on the manuscript, which was written by K.-R.J. and M.G.B.

285

286 **Additional information**

287 The authors declare no competing financial interests. Supplementary information
288 accompanies this paper on www.nature.com/naturematerials. Reprints and permissions
289 information is available online at <http://npg.nature.com/reprintsandpermissions>.
290 Correspondence and requests for materials should be addressed to C.C. or M.G.B.

291

292 **Competing interests**

293 The authors declare no competing financial interests.

294

295 **Methods**

296 **Sample preparation.** The heterostructures were grown on 5 mm × 5 mm quartz
297 substrates by dc magnetron sputtering in an ultra-high vacuum chamber. The chamber
298 was baked out for 10 hours and subsequently cooled with a liquid nitrogen for 2 hour to
299 reach a base pressure better than 5×10^{-6} Pa and a water partial pressure below 10^{-7} Pa.
300 All layers were grown *in-situ* at room temperature. Nb, Ni₈₀Fe₂₀, and Cu (capping layer
301 present on all samples) were deposited at an Ar pressure of 1.5 Pa and Pt at 3.0 Pa. The
302 typical deposition rates were 21.1 nm/min for Nb, 5.1 nm/min for Ni₈₀Fe₂₀, 7.6 nm/min
303 for Pt, and 9.7 nm/min for Cu. Multiple quartz substrates were placed on a rotating
304 circular table which passed in series under stationary magnetrons, so that 5 samples
305 with different layer thicknesses could be grown in the same deposition run. This
306 guarantees that the interface properties of the samples presented are more or less
307 identical. The thickness of each layer was controlled by adjusting the angular speed of
308 the rotating table at which the substrates moved under the respective targets and the
309 sputtering power. The thicknesses of Py, Pt, and Cu layers were kept constant at 6, 5,
310 and 5 nm, respectively, while the thickness of Nb layer varied from 7.5 to 60 nm in
311 order to investigate the variation of FMR linewidth as a function of Nb thickness
312 through the superconducting transition T_c . For the study of spin-sink material
313 dependence (Fig. 3), Ta and W were grown at an Ar pressure of 3.0 Pa whereas Cu
314 (spin sink layer), Ho, and Fe₅₀Mn₅₀ were of 1.5 Pa to keep the interface roughness more

315 or less similar for all samples.

316

317 **Superconducting transition measurement.** DC electrical transport measurements
318 were mostly conducted using a custom-built dipstick probe in a liquid helium dewar
319 with a four-point current-voltage method. The resistance R (of a sample) vs. temperature
320 T curves were obtained while decreasing T . From the T derivative of R , dR/dT , the
321 superconducting transition temperature T_c was denoted as the T value that exhibits the
322 maximum of dR/dT . Note that care was taken to ensure that the applied current $I \leq 0.1$
323 mA had no effect on T_c . For the samples with T_c below 4.25 K, the electrical transport
324 measurements were performed in a closed-cycle cryostat with a ^3He insert capable of
325 reaching 0.3 K. The full set of $R(T)$ curves is included in the Supplementary
326 Information (Sec. S9).

327

328 **Dynamic measurement technique.** The broad-band FMR setup used for this study
329 involves a microwave (MW) source, lock-in amplifier (LIA), and co-planar waveguide
330 (CPW). The MW source whose power is of -20 to $+20$ dBm is connected to a pulse
331 generator so that a MW frequency f_{mw} (in the GHz range) is squarely modulated with a
332 modulation frequency f_{mod} of <1 kHz. The transmitted MW signal through a sample
333 attached onto a CPW is rectified by a MW diode with a bandwidth of 40 GHz. The LIA
334 multiplies the diode voltage with a reference at f_{mod} and integrates the result over a
335 certain time. This results in a DC voltage, only coming from signals having the same
336 frequency as the reference. To obtain each FMR spectrum, this DC voltage was
337 measured while sweeping the external magnetic field (along the film plane direction) at
338 a fixed f_{mw} of 5 to 20 GHz. The MW power was set to 10 dBm for all measurements but

339 taking into account the attenuation through coaxial cables and connectors, the actual
340 MW power absorbed in the sample is expected to be a few mW [see the Supplementary
341 Information (Sec. S11) for discussion about the effect of MW power on the
342 superconductivity of Nb]. Note that in any case, the thickness of Nb layers studied here
343 is much less than the magnetic penetration depth (> 100 nm in thin Nb films)³² and so
344 there is no significant effect of Meissner screening on the local (DC/RF) magnetic field
345 experienced by $\text{Ni}_{80}\text{Fe}_{20}$ below T_c . We employed a vector field cryostat from *Cryogenic*
346 *Ltd* that allows for a 1.2 T magnetic field in any direction over a wide T range of 2 –
347 300 K. Most of the room temperature measurements were performed by using a separate
348 FMR setup capable of a (DC) magnetic field modulation, which provides a better
349 signal-to-noise ratio. Note also that we ensured that there is no fundamental difference
350 in the obtained FMR spectra (at 300 K) between the two setups.

351

352 **References**

353 32. Gubin, A. I., Il'in, K. S., Vitusevich, S. A., Siegel, M. & Klein, N. Dependence of
354 magnetic penetration depth on the thickness of superconducting Nb thin films. *Phys.*
355 *Rev. B* **72**, 064503 (2005).

356 **Data availability.**

357 The data used in this paper can be accessed at <https://doi.org/10.17863/CAM.20719>

358

359 **Figure legends**

360 **Figure 1. Principle of the approach. a-b**, Schematic of magnetization dynamics and
361 resulting spin transport in a symmetric FM/SC/FM (FM: ferromagnet, SC:
362 superconductor) structure above **(a)** and below **(b)** the superconducting transition

363 temperature T_c . Spin-dependent density of states and its occupation in SCs are indicated
 364 by the orange (majority-spin) and cyan (minority-spin) symbols. $M(t)$, J_s , and α_0 (α_{sp})
 365 represent, respectively, the time-varying magnetization vector of the FM, the net spin
 366 current injected from the FM into the SC by spin pumping, and the Gilbert damping of
 367 the FM irrelevant (relevant) to the spin pumping. μ^\uparrow and μ^\downarrow are the spin-dependent
 368 electrochemical potentials. Note that the dark blue indicates the region in which the
 369 superconducting energy gap Δ is suppressed close to the FM/SC interface due to the
 370 (inverse) proximity effect, resulting in the spatial variation of 2Δ over the
 371 superconducting coherence length ξ_{sc} (from the FM/SC interface).

372

373 **Figure 2. Enhanced spin transport in the superconducting state when coupled**
 374 **to strong spin sink. a,** Temperature T dependence of the FMR linewidth $\mu_0\Delta H$ (top)
 375 and the resonance magnetic field $\mu_0 H_{res}$ (bottom) for various Nb thicknesses. The
 376 dashed lines indicate their T_c . **b,** FMR linewidth $\mu_0\Delta H$ as a function of Nb thickness t_{Nb}
 377 of Nb/Ni₈₀Fe₂₀/Nb samples at various T . The solid lines are fits to estimate the effective
 378 values of spin mixing conductance and spin diffusion length using the spin pumping
 379 model^{3,4}. The inset shows data and fits for 300 K. In this inset, the t_{Nb} dependence of the
 380 Gilbert damping constant α (red symbol) is also shown for comparison. **c,** data
 381 equivalent to **(a)** but for Pt/Nb/Ni₈₀Fe₂₀/Nb/Pt spin sink samples. **d,** data equivalent to
 382 **(b)** but for Pt/Nb/Ni₈₀Fe₂₀/Nb/Pt spin sink samples; the same colour coding applies for
 383 the different T . The upper-right inset of **(d)** exhibits the t_{Nb} dependence of the FMR
 384 linewidth difference across T_c , defined as $\mu_0\Delta H(2\text{ K}) - \mu_0\Delta H(8\text{ K})$. The red dashed line
 385 in this inset is a guide to the eyes; the rectangular and diamond symbols represent two
 386 independent sets of the samples grown each in a single deposition run [see
 387 Supplementary Information (Sec. S12) for details]. Error bars denote standard deviation

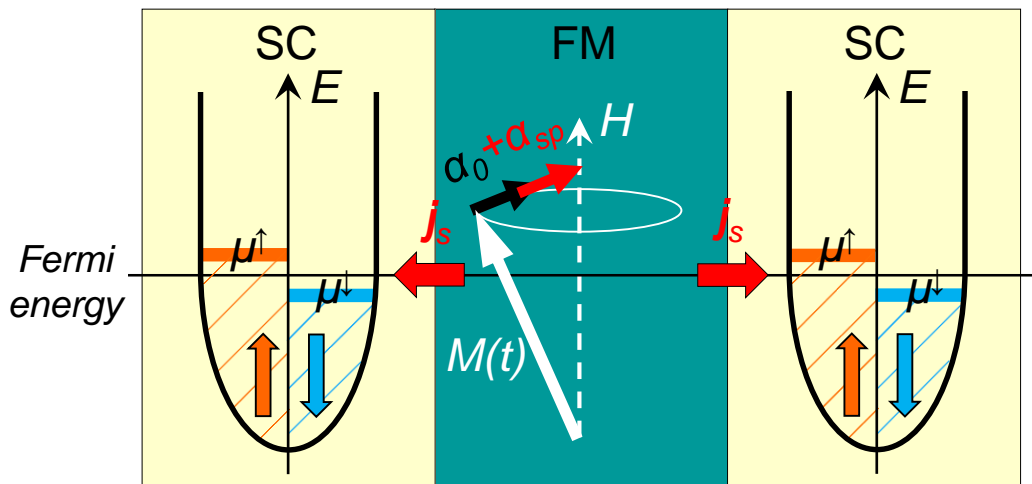
388 of multiple measurements.

389

390 **Figure 3. Enhanced spin transport in the superconducting state enabled by**
391 **spin-orbit coupling (SOC) along with precessing magnetization. a,** FMR linewidth
392 $\mu_0\Delta H$ as a function of the normalized temperature T/T_c for various spin sink materials
393 with a constant thickness of 5 nm, taken at the fixed $t_{\text{Nb}} = 30$ nm and $f = 20$ GHz. The
394 Ref sample is $t_{\text{Nb}} = 30$ from the series shown in Fig. 2a which only has a 5-nm Cu (top)
395 cap layer. **b,** Spin-sink material dependence of the FMR linewidth difference across T_c ,
396 denoted as $\mu_0\Delta H(2\text{ K}) - \mu_0\Delta H(8\text{ K})$. Note that the resonance field $\mu_0 H_{\text{res}} \geq 350$ mT
397 induces a homogeneous magnetization M in Ho (5 nm), enabling to focus on SOC^{26,27}
398 rather than M inhomogeneity^{1,2}. Error bars denote standard deviation of multiple
399 measurements.

400

401

a“Normal” state, $T > T_c$ **b**“Superconducting” state, $T < T_c$ 